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SPHERICAL SHIELDS FOR THE CONTAINMENT OF EXPLOSIONS.(U)

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EDGEWOOD ARSENAL TECHNICAL REPORT
EM-TR-76096

SPHERICAL SHIELDS FOR THE CONTAINMENT OF EXPLOSIONS

By

Kevin P. Nelson

Manufacturing Technology Directorate

March 1977

DEPARTMENT OF THE ARMY
Headquarters, Edgewood Arsenal
Aberdeen Proving Ground, Maryland 21010

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER EM-TR-76096	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SPHERICAL SHIELDS FOR THE CONTAINMENT OF EXPLOSIONS.		5. TYPE OF REPORT & PERIOD COVERED Technical Report, July 1975–September 1976,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Kevin P. Nelson		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Commander, Edgewood Arsenal Attn: SAREA-MT-TS Aberdeen Proving Ground, MD 21010		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS MM&T Project 5761264
11. CONTROLLING OFFICE NAME AND ADDRESS Commander, Edgewood Arsenal Attn: SAREA-TS-R Aberdeen Proving Ground, MD 21010		12. REPORT DATE March 1977
		13. NUMBER OF PAGES 25
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) (12) 24p.		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE NA

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.
Copies available from: National Technical Information Service, Springfield, VA 22151.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Advance technology for suppressive shielding of hazardous production and supply operation.

18. SUPPLEMENTARY NOTES

Advance technology for suppressive shielding of hazardous production and supply operation.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Safety
Suppressive shield
Blast containment
Transportation shield

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Suppressive shields are designed to reduce the effects of an accidental explosion to a safe environment. One of these shields, a two-foot diameter sphere, completely contains the detonation of 1 pound of explosive and will be used to transport or store small quantities of explosives. Two of these shields have been fabricated from different steels and successfully tested, in fact surpassing all design requirements. Both shields have been approved for use in Army Ammunition Plants by the DOD Explosive Safety Board.

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PREFACE

The work presented in this report was authorized under MM&T Project 5761264, Advance Technology for Suppressive Shielding of Hazardous Production and Supply Operation. Work was carried out from July 1975 to September 1976.

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SPHERICAL SHIELDS FOR THE CONTAINMENT OF EXPLOSIONS

I. INTRODUCTION.

The purpose of this report is to describe the design, fabrication, and testing methods used to develop spherical shields to contain the effects of an accidental explosion. The spheres defined were designed for two specific applications, the first being for manual transportation of small quantities of explosives and the second for the storage of laboratory explosive samples.

The shields described in this report were developed under MMT Project 5761264, "Advanced Technology for Suppressive Shielding of Hazardous Production and Supply Operations." The purpose of this program was to develop technology to provide protection from the dangerous effects of an explosive detonation. Suppressive shields in their conception consisted of a series of vented panels in a framework, as shown in figure 1. The shields were designed to attentuate explosive blast pressure and fireball effects and prevent any fragments from escaping the shield.

The suppressive shielding program is divided into several tasks. First, groups of shields designed to contain specific explosive hazards were designed, fabricated, tested, and safety-approved for use in Army ammunition plants. The second portion of the program makes use of test data from the shield groups and other work in the writing of a design handbook. The third segment considers the interface problems involved in the implementation of suppressive shielding technology on various production base modernization and expansion projects.

The spherical shields defined in this report are one of the groups of shields developed, Shield Group 6. Two shields were fabricated and tested, a mild steel shield, called Group 6A in this report, and a stainless steel shield, called Group 6B.

Section II of this report lists design requirements and describes design procedures used. Sections III and IV outline fabrication techniques and test descriptions and results, respectively. Section V lists conclusions derived from the work performed and Section VI gives recommendations.

II. DESIGN REQUIREMENTS AND PROCEDURES.

Design requirements for Shield Groups 6A and 6B were based on a specific application for transporting small quantities of explosive. This application involved the replacement of a cartrac conveyor system by shielded push carts used to transport 19 one-ounce charges of lead azide explosive from a drying facility to a loading facility at Iowa AAP. This shielded cart would eliminate the conveyor system resulting in a large cost saving, would allow greater flexibility in the production rate, and by using the cart for in-process storage, would eliminate several storage barricades.

This shielded cart would be used in day-to-day on-line operations and must be easily pushed by a variety of employees. A 400-pound limit was set for the entire unit and after subtracting the cart and accessories weight, a 200-pound weight limit for the shield was established. The shield must also be able to pass through a standard doorway requiring the unit width to be less than 30 inches. A 24-inch diameter was selected for the shield design.

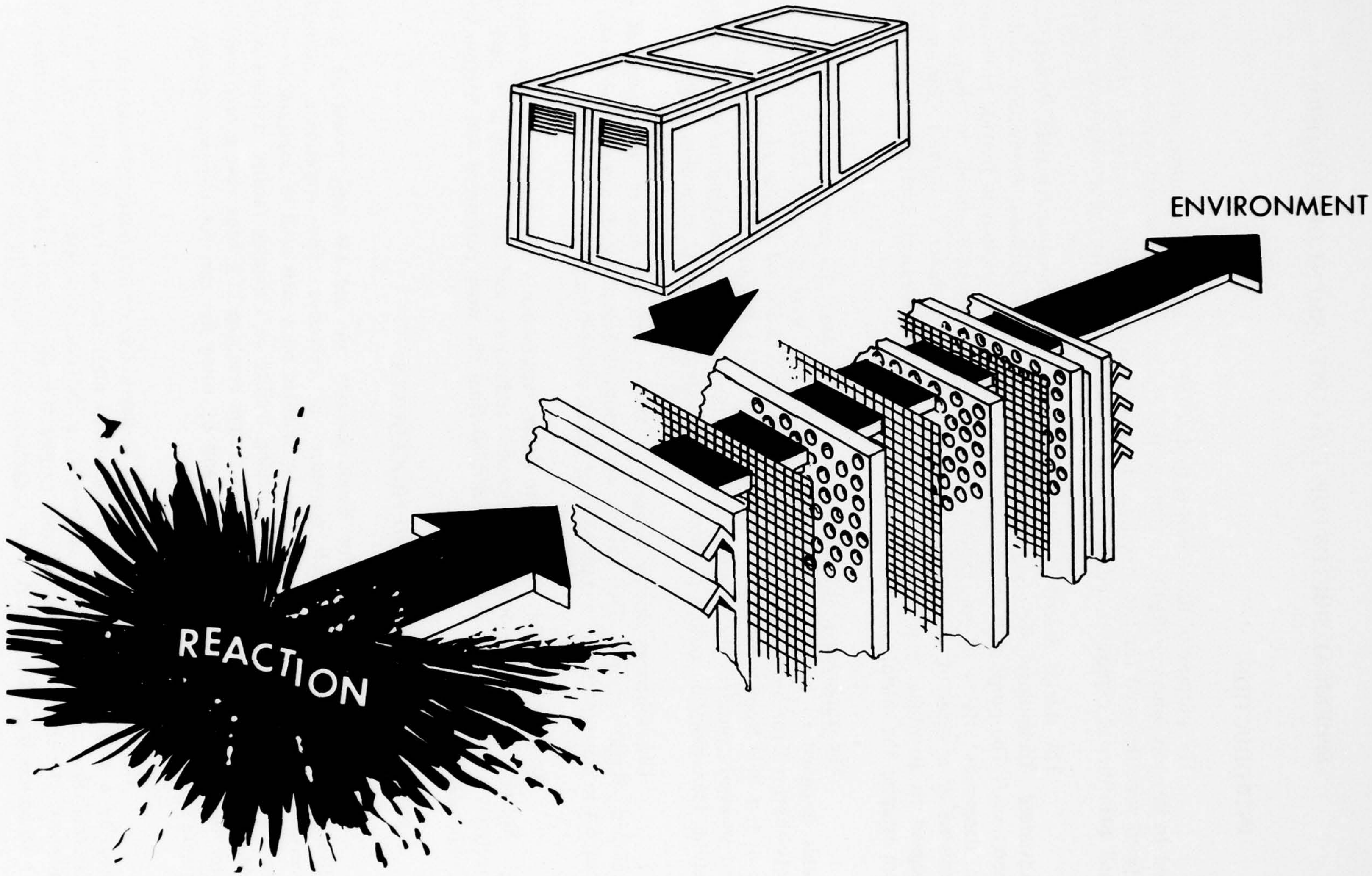

Figure 1. Vented Panel Configuration

The shield must contain the explosive blast effects of 19 ounces of lead azide, such that an operator safe environment is maintained at the operator's position slightly more than 2 feet from the shield. This requires that all fragments be contained in the shield and that the blast overpressure two feet from the shield be less than 5 psi reflected (2.3 psi side-on), which is the eardrum rupture pressure limit as defined in TM 5-1300.[1] In addition, the shield must successfully contain the 19 ounces of lead azide plus a 25% overcharge, or 23.75 ounces, to meet DARCOM safety approval requirements.

The shield must also have an opening large enough to load and unload a rubber cup 3 inches by 2 inches containing one ounce of lead azide. To accommodate this cup, a port opening 7.5-8.0 inches in diameter is required. During operation, the cups of lead azide would be placed remotely on a rotatable carousel inside the shield. The cups would be positioned on this carousel around its periphery. Cups would then be positioned one at a time in front of the port opening for removal after transportation between operations.

Test results from previously tested shields indicated that the venting area of the shield would have to be almost zero in order to reduce the blast overpressure to below 2.3 psi two feet from the shield wall. A solid sphere shield was selected for several reasons. First, fragments are minimal, posing no hazard to the sphere structure. Secondly, a circular carousel must fit in the shield. Thirdly, a sphere is the most efficient structural configuration for containing the blast pressure.

Quasi-static, side-on, and reflected-blast-wave pressures were used in calculating loading on the shield. Quasi-static pressure, the pressure inside a vessel caused by heated, expanded air and gases from an explosion, inside a 24-inch diameter sphere, was calculated using the TM 5-1300 formula:

$$P = 2410(W/V)^{0.72}$$

where

P = Quasi-static pressure in psi

W = Weight of TNT equivalent explosive in pounds

V = Volume of the vessel; in this case, 4.18 ft^3

A TNT equivalency of lead azide of 0.5 was assumed for these calculations as no equivalency tests had been performed prior to the design. A recent report[2] indicated that the TNT equivalency is 0.35. Using the 0.5 TNT equivalency for lead azide, a quasi-static pressure of 695 psi was calculated for the proof charge of 23.75 ounces of lead azide.

Side-on blast pressures and reflected pressures were predicted using Goodman's data.[3] Side-on pressure is the blast overpressure on a surface parallel to the direction in which the blast wave is travelling. Reflected pressure is read behind the reflected blast wave on a surface perpendicular to the direction in which the blast wave is travelling. Both of these pressures vary with scaled distance (Z), which is computed by the formula:

$$Z = \frac{R}{W^{1/3}}$$

where

R = distance from the explosive in feet

where

W = weight of pentolite equivalent explosive in pounds

As Z increases, side-on and reflected pressures decrease.

For the design charge configuration shown in figure 2, scaled distance is computed for a one-ounce charge 3 inches from the shield wall. This gives a scaled distance of 0.794 which predicts a side-on pressure of 1250 psi and a reflected impulse of 119 psi-msec. Even though the shield holds 24 incremental charges for the proof test, the distances between them is sufficient that the overpressure from one charge at any point on the wall has dissipated before the overpressure from the next charge reaches that point. Also, the overpressure at the point between two charges where the overpressures from each will arrive simultaneously is lower than the calculated maximum of 119 psi-msec.

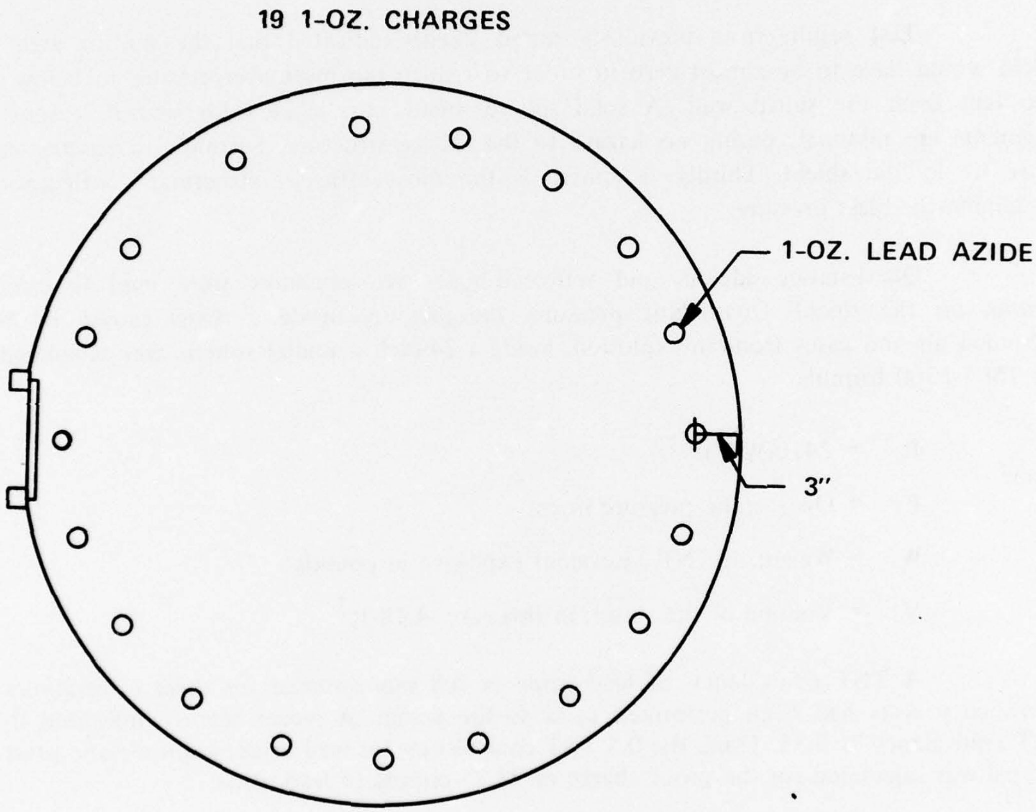

Figure 2. Charge Configuration

Calculations were performed to determine what thickness of steel in a 24-inch diameter sphere would contain the explosive blast. Calculation using the formula:

$$t_s = \frac{pa_s}{2\sigma_s}$$

where

t_s = thickness of the spherical shell

p = static internal pressure, 695 psi

a_s = internal radius of the sphere, 12 inches

σ_s = yield strength of the sphere, 30,000 psi (minimum) for steel

leads to a thickness of 0.139 inches. A 0.25-inch thick sphere was chosen for two reasons. First, 0.25-inch thick is a standard plate easily obtainable, and second, the weight of a 24-inch diameter, 0.25-inch thick sphere would be 131 pounds, well below the maximum design weight of 200 pounds. The additional strength of the shield will counteract any material flaws in the steel. Predictions for the sphere's thickness were performed using only quasi-static pressures and some additional strength will be needed to contain the effects of the reflected blast pressures.

Several factors were taken into consideration in designing the door and the port opening:

a. The perimeter of the port opening must be circular so that no corners exist where stress concentrations can develop.

b. The perimeter of the circular port opening must be reinforced with a ring both to take the force exerted on it by the door and to absorb the loads in the sphere concentrated on the periphery of the opening.

c. The flat door plate must be strong enough to withstand the blast effects without failure.

d. The bearing area between the door and the reinforcing ring must be sufficient to transmit the load from the door to the ring.

e. The door must be inside the shield so that it is forced against the shield by the blast.

f. The door must seal tightly to limit overpressures outside the shield.

Equations provided by Trott[4] were used to calculate the design parameters for the door and the port opening. (These formulas design the door and port to be as strong as the sphere. As the sphere is stronger than necessary, so are these parameters.) The bearing overlap (b) between the door and the ring was calculated using:

$$b = (\sigma_s/\sigma_b)\ (a_d/a_s)t_s$$

where

σ_b = the lower of the compressive yield-stress values for the door and the ring materials, 30,000 psi.

a_d = radius of the port.

The thickness of the flat door plate (td) was calculated using the formula:

$$t_d = \left[\frac{\frac{3}{4}(3+\gamma)\, a_o^2}{\frac{a_s}{t_s} - y_z\left(\frac{3+\gamma}{1-\gamma}\right)} \right]^{1/2}$$

where

$$\gamma = \text{Poisson's ratio, 0.27 for steel}$$

$$a_o = a_d + b/2$$

The cross-sectional area (A) of the port reinforcing ring was designed using the formula:

$$A = \frac{a_s t_s}{1-\gamma} \cos \phi \ \sin \phi$$

where

$$\phi = \sin^{-1} (a_o/a_s)$$

III. FABRICATION SPECIFICATIONS AND TECHNIQUES

Two similar shields were designed and fabricated. The first, shield 6A, was made of 1010-1020 low carbon mild steel with the following material properties:[5]

Young's Modulus	30×10^6 psi
Yield Strength	55,000 psi

Shield 6A is illustrated by photograph in figure 3 after testing and engineering drawing in figure 4. This shield was fabricated from two 0.25-in-thick flat plates which were spun into hemispheres and welded together so that the weld was on the horizontal axis. A 1.5-in-wide doubler plate was added on the outside of the shield covering the weld for additional strength. A 0.25-in-thick steel band was added inside the shield to absorb the localized effects of the incremental charges. A 0.25-in-diameter hole was drilled in the base of the shield for the passage of detonator wires.

A 7.5-inch-diameter port opening was cut into the upper hemisphere centered 45 degrees above the horizontal axis. A reinforcing ring was added around this port opening (calculated cross section for the ring of 1.228 inches^2) which was of 10.5-inch-outer-diameter, 8.0-inch-inner-diameter, 0.75-inches-thick (cross-sectional area with the sphere section of 1.25 inches^2). A 0.375-inch-thick, 8.0-inch-diameter door hinged at the top to swing inward was used to close the port. This door is thinner than the calculated thickness of 0.89 inches, but it is reinforced with cross members for additional strength and is therefore lighter for easier opening and closing. The disadvantage of this design is that considerable volume of the sphere is lost for use because of the large swing area of the door. The bearing surface between the door and the port is 0.25 inches wide, much greater than the calculated value, 0.043 inch.

Dye penetration tests were conducted on all welds on shield 6A and any faults were rewelded. The entire sphere was heat-treated to relieve any stress concentrations caused by the welding.

Figure 3. Shield 6A

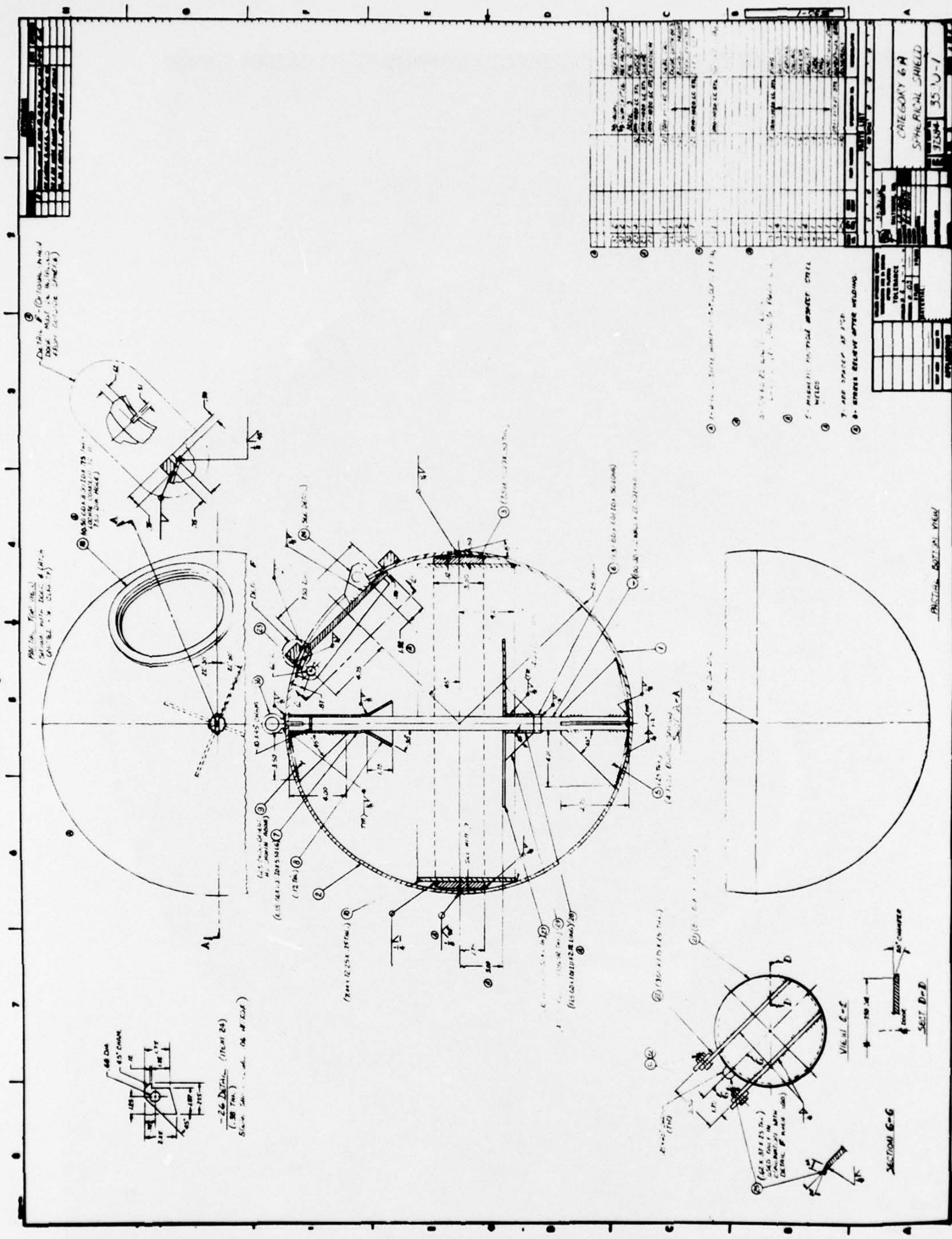

Figure 4. Shield 6A Drawing

A second shield, 6B, was designed using type 304 stainless steel having the following properties:[5]

Young's Modulus	28×10^6 psi
Yield Strength	85,000 psi

Shield 6B is pictured in figure 5 and shown in engineering drawings in figures 6, 7, and 8. This shield was also spun into hemispheres from 0.25-inch-thick plate and the hemispheres were welded together on the vertical axis. A 1.5-inch-wide doubler plate was added over the weld for additional strength. No band was added inside the shield to absorb localized effects of an explosion as tests on shield 6A showed this to be unnecessary.

The port opening is centered on the horizontal axis of the shield, centered in one of the hemispheres. It is reinforced by an 8.0-inch inner-diameter, 10.25-inch outer-diameter, 1.10-inch-thick ring (1.4878 inches^2 cross-sectional compared to the calculated value of 1.30-inch^2). The port is closed by an 8.50-inch-diameter, 0.75-inch-thick door (calculated thickness of 0.89 inches). The bearing overlap of 0.25 inches is greater than the 0.043-inch overlap calculated. This door is connected to struts that are hinged on the vertical axis of the shield so that the door swings open sideways, along the shield wall. This maximizes the usable volume within the sphere. A second door, 0.50-inches-thick and 10.00-inches in diameter, is hinged to swing outward. The two doors are cam-latched together so that neither can move during an explosive detonation. A 0.125-inch-diameter hole was drilled through the doors for the passage of detonator wires.

Dye penetration tests were conducted on the welds of the shield but no heat treating was done because this causes brittleness in stainless steel.

IV. TEST DESCRIPTIONS AND RESULTS.

Shield 6A was tested using 50/50 pentolite (TNT equivalency of 1.17) in place of the ultrasensitive lead azide. Test charges consisted of 0.5-ounce incremental charges placed around the horizontal periphery of the shield, 3 inches from the wall, to simulate the charge placement in the candidate operation. The incremental charges were strung on primacord to insure that all would detonate in a sequential order. All tests using a greater quantity than the 25-percent overcharge proof test (figure 2) were of one central charge. A list of the tests conducted in the order in which they occurred is presented in table 1.

Peak reflected pressures and quasi-static pressures were measured by two piezo-electric transducers located on the horizontal axis of the shield 90 degrees on either side of the port opening (depicted by arrows on figure 3). Two uniaxial metal-film gauges were used to measure strain (depicted by stars on figure 3), one on the sphere itself and one on the doubler plate covering the weld connecting the two hemispheres. Two gages recorded side-on blast overpressures outside the shield, one gage was two feet in front of the door and level with it. The other was 90 degrees to the right and 2 feet from the shield.

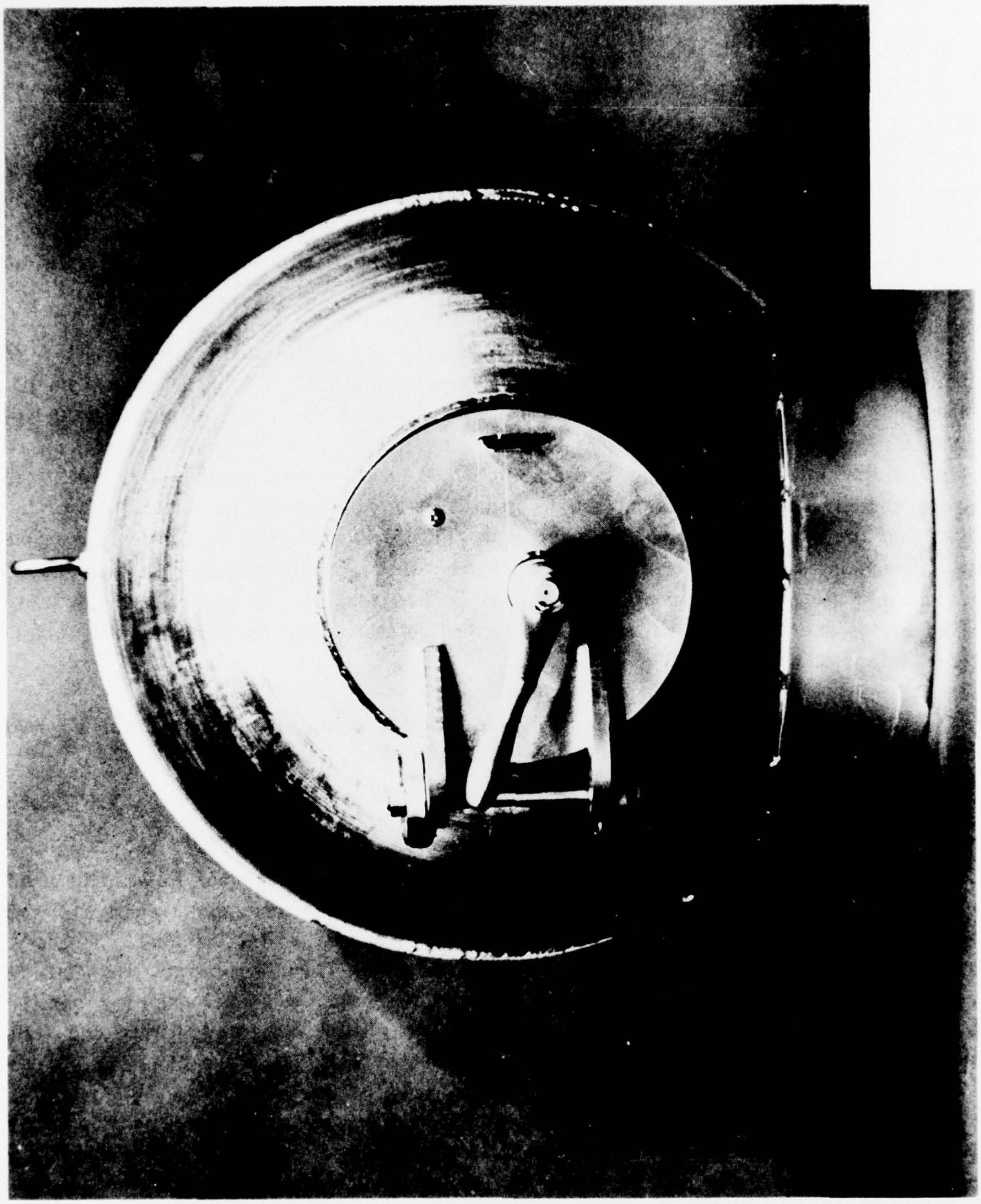

Figure 5. Shield 6B

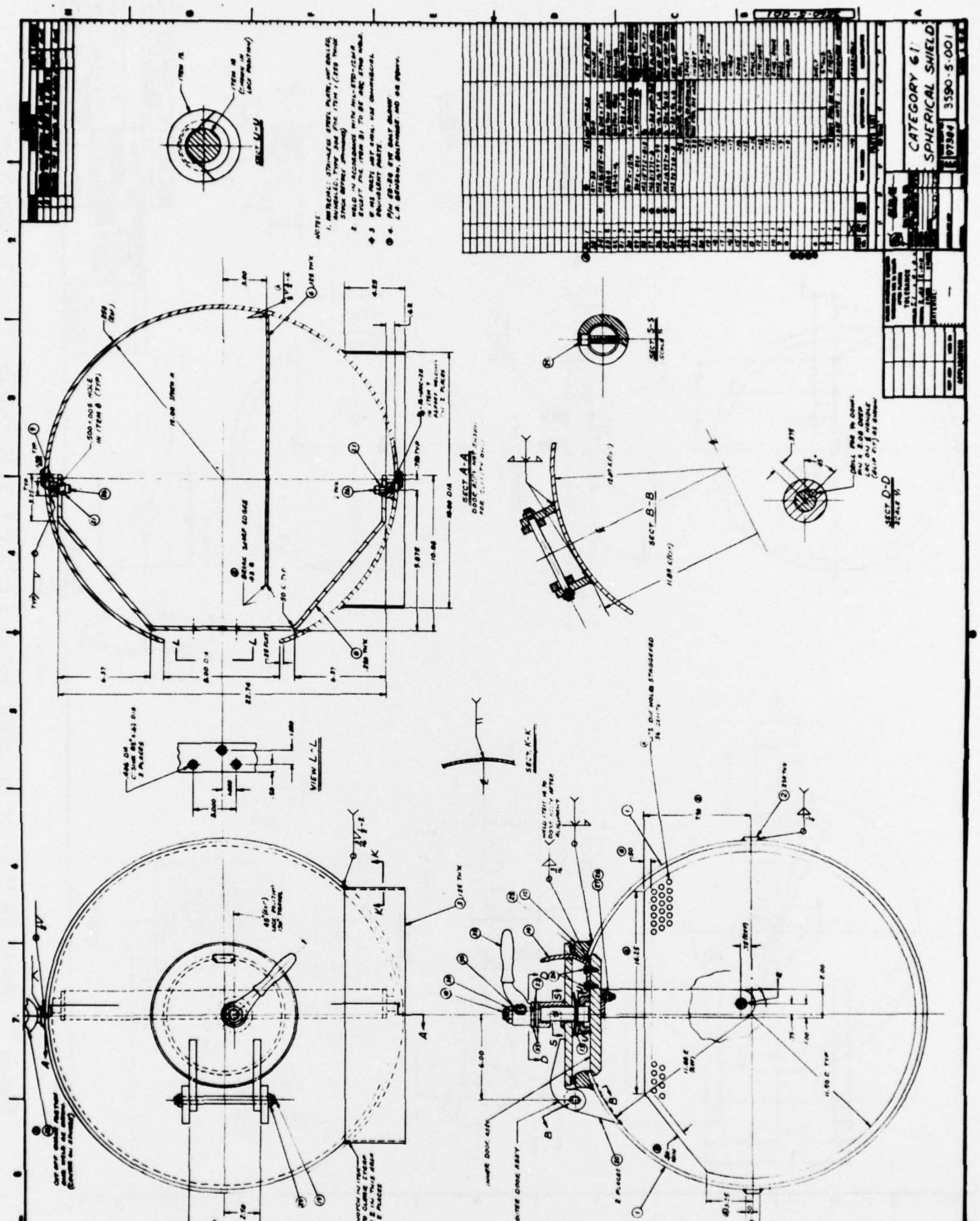

Figure 6. Shield 6B Drawing Including Sections A-A, D-D, K-K, L-L, S-S, and U-U

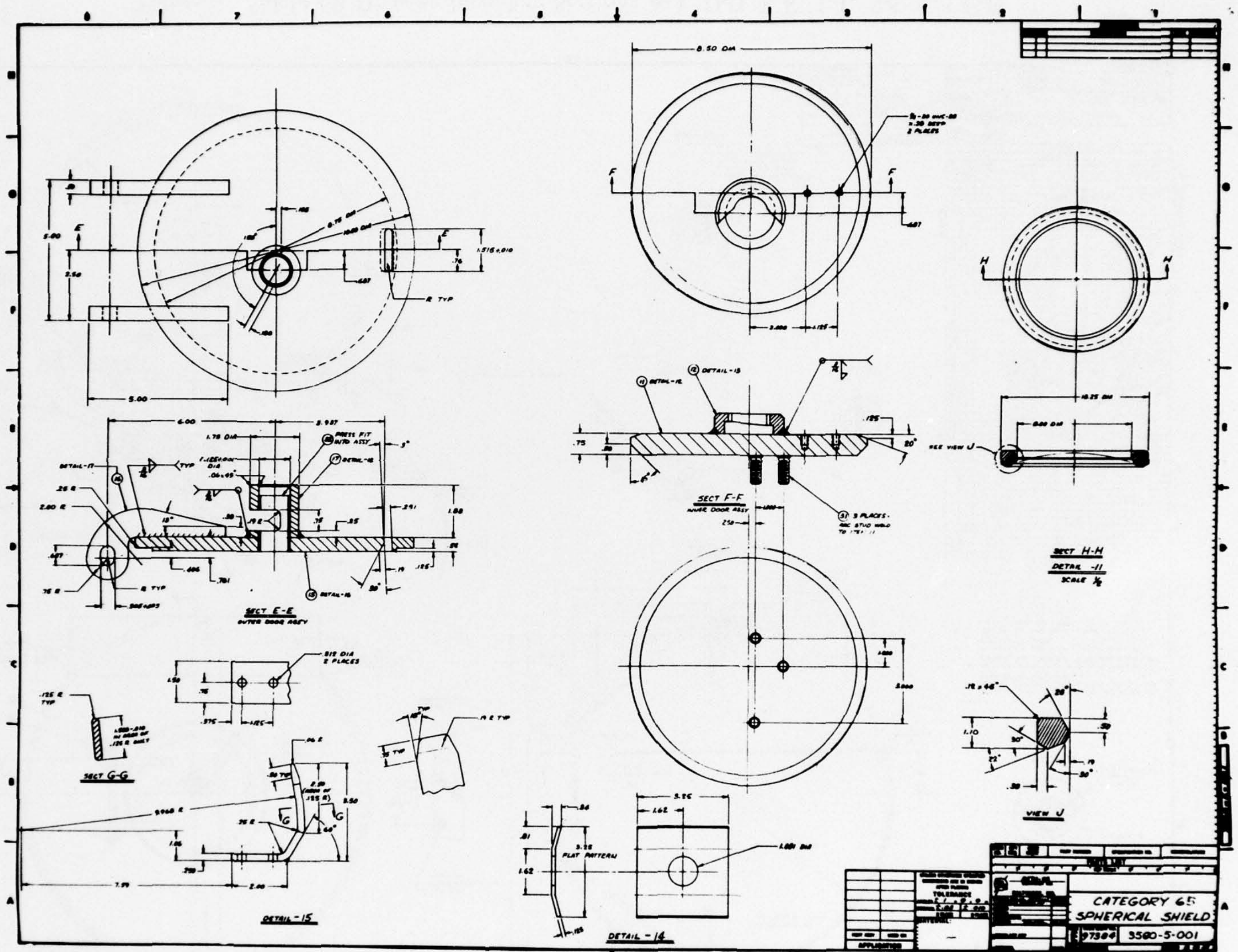

Figure 7. Shield 6B Drawing Including Sections E-E, F-F, H-H, Details 14 and 15, and View J

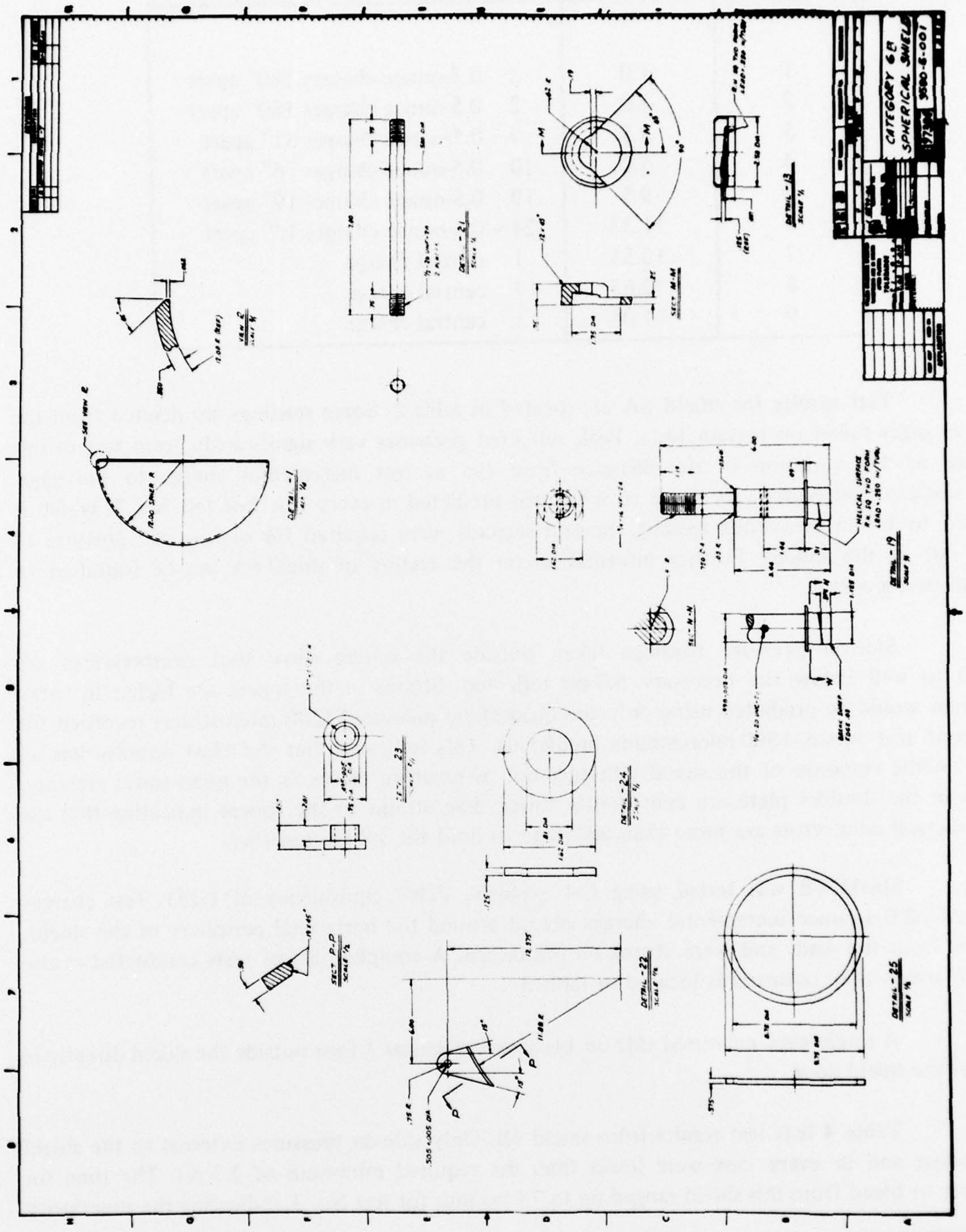

Figure 8. Shield 6B Drawing Including Details 1, 13, 19, 21 through 25, Sections M-M and P-P, and View R

Table 1. Test Descriptions for Shield 6A

Test No.	Quantity	Description
	oz	
1	1.0	2 0.5-ounce charges 180° apart
2	1.0	2 0.5-ounce charges 180° apart
3	3.5	7 0.5-ounce charges 51° apart
4	5.0	10 0.5-ounce charges 36° apart
5	9.5	19 0.5-ounce charges 19° apart
6	11.33	24 ~ 0.5-ounce charges 15° apart
7	12.55	1 central charge
8	12.63	1 central charge
9	17.04	1 central charge

Test results for shield 6A are located in table 2. Some readings are deleted from the table as gages failed on certain tests. Peak reflected pressures vary significantly from test to test because of the variation in the distance from the nearest incremental charge to the gage. Quasi-static pressures are very close to what was predicted in every case but test No. 7, which is believed to be an erroneous reading. Several seconds were required for quasi-static pressure to bleed out of the sphere. Further information on the testing of shield 6A can be found in an unpublished report.*

Side-on pressure readings taken outside the sphere show that overpressures are limited to well below the necessary 5.0 psi reflected. Strains in the sphere are higher in every case than would be predicted using only the quasi-static pressure (2200 microstrains recorded for the proof test versus 1800 microstrains predicted). This indicates that the blast impulse has an effect on the response of the shield although not as great an effect as the quasi-static pressure. Strains in the doubler plate are consistently lower than strains in the sphere indicating that the hemispherical connectors are more than adequate to hold the sphere together.

Shield 6B was tested using C-4 explosive (TNT equivalency of 1.25). Test charges consisted of 0.4-ounce incremental charges placed around the horizontal periphery of the shield, 3 inches from the wall, and were strung on primacord. A complete list of tests conducted in the order in which they occurred is located in table 3.

A single gage measured side-on blast overpressures 1 foot outside the shield directly in front of the shield door.

Table 4 lists test results from shield 6B. Only side-on pressures external to the shield were taken and in every case were lower than the required minimum of 2.3 psi. The time for pressures to bleed from this shield ranged up to 75 seconds for test No. 3, indicating the superiority

*Jackson, Willis. Ballistics Laboratory Report. Category 6 Suppressive Shield Tests. Aberdeen Proving Ground, MD.

Table 2. Test Results for Shield 6A

	Test No.								
	1	2	3	4	5	6	7	8	9
Peak reflected pressure	2800	3500	1500	1400	2000	- -	9000	6600	-
Quasi-static pressure (psi)	175	115	190	340	490	600	1000	700	- -
Pressure outside shield (psi) door	1.0	0.25	0.15	0.4	0.35	0.25	-	0.2	0.95
Pressure outside shield (psi) side	1.3	6.0	0.20	0.75	0.95	0.85	-	0.4	1.05
Strain in sphere (microstrains)	1300	850	900	2000	1900	2200	2500	2800	4000
Strain in doubler plate (microstrains)	350	250	400	500	650	500	1500	1650	2200

Table 3. Test Descriptions for Shield 6B

Test No.	Quantity oz	Description
1	1.76	1 central charge
2	3.52	1 central charge
3	8.81	1 central charge
4	8.81	1 central charge
5	10.29	24 0.429-ounce charges 15° apart
6	24.00	24 1.0-ounce charges 15° apart

of shield 6B in reducing blast overpressures. Test No. 4 was performed with the outer shield door open, indicating that a second door is unnecessary for the shield to attentuate blast overpressures. Test No. 6 failed the shield, splitting it at the weld connecting the two hemispheres. Inspection showed that failure resulted from the lack of a full penetration weld at one point.

Table 4. Test Results for Shield 6B

Test No.	Pressure 1 Foot from Shield Door (psi)
1	Negligible
2	0.1
3	0.3
4	0.4
5	0.17
6	Shield failed

A second shield, identical to shield 6B, was fabricated and hydrostatically tested to 1400 psi. This was the highest test pressure possible without yielding the shield. The test pressure was also higher than the 1354 psi quasi-static pressure predicted for the 24-ounce C-4 test that failed the previous shield. The hydrostatically tested shield is currently being used as a storage shield for explosive laboratory samples.

V. CONCLUSIONS.

Spherical shields work well for containing the blast effects of an explosive detonation. In theory, spheres are the lightest and smallest shields possible to contain a given quantity of explosives. The fact that the entire spherical shell is in tension, where steel has its maximum strength, accounts for this.

Several limitations exist in applying spherical shields. Spheres should only be used to shield detonations where fragments are minimal. Fragments would damage the shield, causing stress concentrations at the point of impact. This could lead to catastrophic failure of the shield.

The greatest limitation for using spheres for explosion containment vessels is the lack of economical techniques for the fabrication of reliable spheres. Hemispheres can only be spun or explosively formed up to a diameter of approximately 12 feet. Welding techniques are the limiting factors in determining the strength of a sphere as shown in the failure of shield 6B at a weld. This, in part, results because no methods are available to weld on the inside of a very small sphere.

Shield 6B is superior to shield 6A in many respects. The stainless steel from which it is constructed has greater strength, and is more corrosion resistant. The door design of shield 6B is also superior to that of shield 6A as it maximizes the usable volume within the shield.

Both shields tested have been approved for use by ARMCOM Safety, DARCOM Safety, and the DOD Explosives Safety Board for use in transporting or storing explosives.

VI. RECOMMENDATIONS

Spherical shields are a cost effective method of containing the effects of an explosive detonation. It is recommended that spheres be used wherever possible to counteract explosions, especially in the transportation or storage of small quantities of explosive.

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